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MULTI-CHANNEL SEARCH FOR MINIMAL SUPERGRAVITY AT $p\bar{p}$ and e^+e^- COLLIDERS

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Abstract

We examine the phenomenology of minimal supergravity models, assuming only that the low energy theory has the minimal particle content, that electroweak symmetry is radiatively broken, and that R-parity is essentially conserved. After delineating regions of supergravity parameter space currently excluded by direct particle searches at LEP and the Tevatron, we quantify how this search region will be expanded when LEP II and the Tevatron Main Injector upgrades become operational. We describe how various experimental analyses can be consistently combined within a single framework, resulting in a multi-channel search for supersymmetry, but note that this analysis is sensitive to specific assumptions about physics at the unification scale.

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Grand Unified Theories (GUTs) [1] provide an attractive synthesis of all gauge interactions. A striking prediction of these models is that the proton is unstable. While the observed stability of the proton can be understood if the GUT scale $M_X \gtrsim 10^{16}$ GeV, the origin and stability of the tiny ratio $M_W/M_X \sim 10^{-14}$ remain unexplained. Supersymmetry (SUSY) [2] provides an elegant mechanism for the stability of the hierarchy between the two scales provided that supersymmetric particles are lighter than ~ 1 TeV. More recently, the realization [3] that the precision measurements of the gauge couplings in experiments at LEP are consistent with the simplest SUSY SU(5) GUT (with $M_{SUSY} \sim 1$ TeV) but *incompatible* with minimal non-SUSY SU(5) has motivated many authors [4] to reexamine the expectations of sparticle masses within the theoretically appealing, and relatively strongly constrained, supergravity (SUGRA) framework. Studies of nucleon decay [5] as well as the collider phenomenology [6] of these models have also appeared.

Part of the appeal of these models lies in their economy. The masses and couplings of all the sparticles are fixed in terms of just four additional parameters, renormalized at some ultra-high scale at which the physics is very simple. These parameters may be taken [2] to be the common values of soft SUSY-breaking trilinear and bilinear couplings (A_0 and B_0), a common SUSY-breaking scalar mass (m_0), and a common SUSY-breaking mass for the gauginos of the unbroken grand unified group ($m_{1/2}$). For phenomenological analyses, however, masses and couplings renormalized at the weak scale are required. These can be readily obtained from the unification scale parameters using renormalization group (RG) techniques [7]. This RG evolution leads [2] to calculable splittings between the masses of the gluinos and the electroweak gauginos and between the squarks and sleptons. Unlike third generation sfermions, the first two generations of squarks are approximately degenerate, consistent with the absence of flavor-changing neutral currents in the K-meson sector. A particular attraction of this framework is that electroweak gauge symmetry is automatically broken down to electromagnetism when the Higgs doublet masses are evolved down to the weak scale.

Without SUGRA unification, the Minimal Supersymmetric Standard Model (MSSM) requires a plethora of input parameters, making experimental analyses difficult. While SUGRA GUTs indeed provide an economic framework, we recognize that the assumptions about the physics at ultra-high energy scales may prove to be incorrect and that the unification of gauge couplings suggested by LEP experiments may turn out to be a coincidence. Our approach here is to take this unification seriously and to explore implications of SUGRA models for experiments at the Tevatron and LEP II. We shall assume that the low energy theory has the minimal particle content, that electroweak symmetry is radiatively broken, and that R-parity is essentially conserved. To leave our analysis as general as possible [8], however, we do not commit to a particular GUT group [9], and hence we do not include any constraints from nucleon decay or Yukawa coupling unification. Also, we do not incorporate any fine-tuning constraints. These constraints are somewhat subjective and only serve to yield upper limits on sparticle masses. Finally, we do not include dark matter constraints since these can be simply evaded, *e.g.* by allowing a small R-parity violation which would have no implication for collider experiments. Our purpose is to study the correlations between various experimental searches for supersymmetric particles arising from the fact that the masses and mixing patterns of all the sparticles are determined by just four additional SUSY parameters. If SUSY particles are ultimately discovered, a study of their properties

will allow us to test our underlying assumptions.

Toward this end, we have constructed a program to numerically solve the RG equations (RGE) of the MSSM, implementing SUGRA relations mentioned above as boundary conditions at the scale M_X where the running weak SU(2) and hypercharge gauge couplings come together. We use the one-loop equations except for gauge couplings, for which we include two-loop terms. We also include threshold corrections due to various sparticle contributions entering the gauge coupling RGE's. The weak scale mass parameters, m , are taken to be their running values evaluated at the scale $Q = m$; *i.e.*, they are solutions of $m = m(m)$. We convert the running masses of the top quark [10] and gluino [11] to the corresponding physical (pole) masses. After solving the RGE's, we use the evolved parameters to obtain the scalar potential at the scale M_Z . As emphasized in Ref. [12], the results obtained using the tree-level potential are very sensitive to the scale at which the potential is evaluated. This situation is ameliorated by including one loop corrections from the large top and also bottom Yukawa interactions (these are important when $\tan \beta$ is large) to the potential. In practice, we use the two conditions obtained by minimizing the one-loop effective potential with respect to the Higgs fields to eliminate B_0 in favor of $\tan \beta$, the ratio of the Higgs field vacuum expectation values, and to determine (up to a sign) the superpotential Higgsino mass parameter, μ , at the weak scale. Finally, the effective potential can also be used to determine the pseudoscalar mass m_{H_p} , which, in turn, fixes the other Higgs boson masses. The entire procedure is then iterated until stable results are obtained.

The weak scale squark, slepton and gaugino masses, the A -parameters, and the values of μ , m_{H_p} , and $\tan \beta$ can be used as inputs for ISAJET [13] to compute the masses and mixing patterns of charginos and neutralinos, third generation sfermions and Higgs boson scalars, and their production cross sections and decay patterns relevant for phenomenology. We have incorporated our supergravity RGE solution into ISAJET 7.10. We suggest that a good way to combine the results of different searches for SUSY is to express them as limits in the $(m_0 - m_{1/2})$ plane for several choices of the other SUGRA parameters, *e.g.*, $\tan \beta = 2, 10$, and $A_0 = 0, \pm 2m_0$. However, we urge the reader to keep in mind that the framework depends on assumptions about physics at the scale M_X . For instance, SUGRA models predict a specific form for the squark-slepton mass splitting and the splitting amongst the various squarks. Also, they generally predict that $|\mu|$ is considerably larger than SUSY breaking electroweak gaugino masses, so that lighter charginos and neutralinos are gaugino-like; this has important implications [14] for sparticle decay patterns. We distinguish such SUGRA assumptions from *e.g.* the assumed unification of gaugino masses which follows from grand unification, and stress that analyses [15] with “MSSM input parameters” not correlated as in SUGRA models are also necessary since these serve to illustrate the sensitivity of the signals to unification scale assumptions, specific to supergravity.

We now turn to a discussion of existing and expected SUSY limits in the SUGRA framework as a function of m_0 , $m_{1/2}$, A_0 , $\tan \beta$, $\text{sgn } \mu$, and m_t . Throughout this paper, we take $m_t = 170$ GeV, as suggested by the recent [16] analysis by the CDF collaboration. Our results, for $A_0 = 0$ (this does *not* mean that the weak scale parameter A_t vanishes) and $\tan \beta = 2$ are shown in the $(m_0 - m_{1/2})$ plane in Fig. 1 for (a) $\mu < 0$, and (b) $\mu > 0$. The physical gluino mass (for $m_0 = 500$ GeV) is also shown. The shaded region is excluded by theoretical considerations: in this region, the minimization conditions with the correct value of M_Z require $\mu^2 < 0$ (so that the correct electroweak symmetry breaking is not obtained),

charge or color breaking minima occur, or (as in the protrusion labeled LSP) the lightest supersymmetric particle (LSP) is charged or colored (or the sneutrino), which is not allowed by cosmology assuming the LSP is sufficiently long-lived. While this last constraint could be avoided by allowing for some R-parity violation, the region is also already excluded by experimental constraints as discussed below.

The region below the solid lines in Fig. 1 is excluded by experiments at LEP and the Tevatron. We include the following existing results:

1. Bounds [17] on scalar particle masses from non-observation of signals in Z decays at LEP. Exclusive searches lead to a lower limit of about $M_Z/2$ on the charged scalar masses while the invisible width of the Z boson results in a comparable bound on the sneutrino mass. For clarity, we have only shown the boundary (labeled $\tilde{\nu}(43)$) of the region where $m_{\tilde{\nu}} > 43$ GeV.
2. The LEP bound $m_{\tilde{W}_1} > 47$ GeV on the mass of the lighter chargino.
3. The bound $m_{H_\ell} \gtrsim 60$ GeV on the mass of the lighter Higgs boson. We have checked that the heavier Higgs boson masses exceed 200–300 GeV along the boundary of this region, so that H_ℓ is approximately the Standard Model (SM) Higgs boson so that limits from experimental searches [18] for H_{SM} , are also approximately valid in the SUGRA scenario.
4. The region labeled \cancel{E}_T recently excluded by the D0 Collaboration from the non-observation of an excess of \cancel{E}_T events from squark and gluino production at the Tevatron [19]. To obtain this boundary [20], we have converted the boundary of the excluded region in the $(m_{\tilde{g}} - m_{\tilde{q}})$ plane shown in Ref. [19] to the corresponding boundary in the plane of Fig. 1. For $\mu > 0$ this \cancel{E}_T region would fall entirely within the excluded region of LEP, and hence, is not shown.

The cross-hatched line summarizes the boundary of the parameter plane excluded by current constraints.

In the near future, the energy of LEP will be upgraded to beyond the WW threshold. Charged sparticles [21] and Higgs bosons [22] with masses up to about 90 GeV should then be detectable. Below the dashed-dotted lines labeled $H_\ell(90)$ (in Fig. 1a, H_ℓ is lighter than 90 GeV over the whole plane), $\tilde{\ell}_R(90)$ and $\tilde{W}_1(90)$, the corresponding particles are lighter than 90 GeV, so that these lines roughly denote the boundary of the parameter space that will be probed by direct sparticle searches at LEP II. After the main injector becomes operational, the search for multijet plus \cancel{E}_T or multilepton events at the Tevatron should probe gluino masses up to about 250–300 GeV [23], depending on $m_{\tilde{g}}$. Also, Tevatron experiments should be sensitive to clean high p_T isolated trilepton signals from $\tilde{W}_1 \tilde{Z}_2$ production [14,24,25]. The sensitivity is larger for small values of m_0 for which the sleptons are much lighter than squarks, so that the leptonic decays of the neutralino, and sometimes, even of the chargino are enhanced [14].

The efficiency for detecting these trilepton events is sensitive to the kinematics of the chargino and neutralino decays. We have used ISAJET to perform a Monte Carlo study of this signal for various values of $(m_0, m_{1/2})$ in Fig. 1, using the cuts described in Ref. [24] appropriate for the Tevatron. For $m_{1/2} = 100$ GeV, and for $m_0 = 100, 150$ and 500 GeV

(*i.e.* well away from the kinematic boundary for two-body decays of \tilde{W}_1 or \tilde{Z}_2), which yield $m_{\tilde{W}_1} \simeq m_{\tilde{Z}_2}$ ($\simeq 2m_{\tilde{Z}_1}$) = 94–100 GeV in Fig. 1a, we find an efficiency of $\sim 40\%$, consistent with previous studies [25] of the signal. Except for the $m_0 = 100$ GeV case where it falls to 31%, this efficiency increases by about 10% when $m_{1/2}$ is increased to 140 GeV, but then $\sigma(\tilde{W}_1 \tilde{Z}_2)$ is considerably smaller. For $(m_0, m_{1/2}) = (20, 100)$ GeV where the charginos and neutralinos decay via two-body modes, the efficiency is also $\sim 50\%$. We have also computed the efficiency for $(m_0, m_{1/2}) = (80, 100)$ GeV, a point very close to the dashed boundary, and find it to be only 1%, primarily due to the soft lepton from $\tilde{W}_1 \rightarrow \tilde{\nu}_L \ell$ decay, which has a branching fraction of almost 90%. Finally, we have computed the efficiencies for $m_{1/2} = 120$ GeV and $m_0 = (20, 40, 300)$ GeV in Fig. 1b where the chargino and neutralino masses are somewhat smaller. For the $m_0 = 20$ GeV case, we find an efficiency of about 30%; however, for $m_0 = 40$ GeV, it falls to just 2%: this is because the Q -value for the two body decay $\tilde{Z}_2 \rightarrow \tilde{\ell}_R \ell$, which has a branching fraction of 99%, is only 5 GeV. For the $m_0 = 300$ GeV case the efficiency is $\sim 27\%$, somewhat smaller than the 3-body decay cases of Fig. 1a.

Thus, for most sets of SUGRA parameters, the trilepton detection efficiency ranges between 30–50% depending on the parameters for charginos and neutralino masses in the range 65–130 GeV. By the end of the current Tevatron run, it is expected that the CDF and D0 experiments will collectively accumulate a data sample exceeding 100 pb^{-1} . Since the physics backgrounds to the trilepton signal are tiny [14,24,25], we expect that trilepton cross sections as small as 200 fb , (corresponding to 5–10 events/100 pb^{-1}) should lead to detectable signals. The boundary of this region, computed using ISAJET 7.10 with CTEQ2L [26] structure functions, is shown by the dashed line labeled $3\ell(200 \text{ fb})$. Since the signal is essentially rate limited, we estimate that the trilepton cross sections an order of magnitude smaller should be detectable after the main injector commences operation. This expands the signal region to below the dashed line labeled $3\ell(20 \text{ fb})$. It is interesting to see that the trilepton signal may be observable for chargino masses well in excess of the LEP II reach (particularly for smaller values of m_0) in keeping with previous studies [14,24,25]. Finally, we note that the spoiler modes $\tilde{Z}_2 \rightarrow \tilde{Z}_1 H_\ell$ and $\tilde{Z}_2 \rightarrow \tilde{Z}_1 Z$, which become accessible above the horizontal dotted lines, do not significantly limit the observability of the trilepton signal for the range of parameters in this figure.

In order to illustrate how the phenomenology is altered when we change A_0 and $\tan \beta$, we repeat this analysis in Fig. 2 for (a) $A_0 = -2m_0$, $\mu > 0$ and (b) $\tan \beta = 10$, $\mu < 0$, with all other parameters as in Fig. 1. The most obvious difference in Fig. 2a is the large shaded region excluded by “theory”. In the large parabolic region for $m_0 > 150$ GeV, the large mixing between the scalar top states induced by the large value of A_0 results in $m_{\tilde{t}_1}^2 < 0$, so that the symmetry is improperly broken. In the slanted-line shaded region with small values of $m_{1/2}$, \tilde{t}_1 is not tachyonic, but the parameter $m_{\tilde{t}_R}^2 < 0$. While this may be physically allowed (as long as it is positive at scales where electroweak symmetry remains unbroken also in the Higgs sector), we caution ISAJET users that this causes technical problems in the program. Fortunately, this region is excluded by LEP constraints. Below the dashed-dotted line labeled $\tilde{t}_1(90)$, the lighter of the two scalar top states should be detectable either at LEP II or at the Tevatron as discussed in Ref. [27]. Also, there is a small sliver of the parameter space (not shown) above the parabolic shaded region where the \tilde{t}_1 would be the LSP, and another small region where the stop would have been detectable at LEP. Fig. 2a, otherwise, resembles Fig. 1b, where μ is also positive, and except for the fact that the \tilde{t}_1 may

also be experimentally accessible, the phenomenology is qualitatively very similar in the two cases. It should also be noted that the 3ℓ signal from $\tilde{W}_1\tilde{Z}_2$ production will be strongly suppressed when the decay $\tilde{W}_1 \rightarrow \tilde{t}_1 b$ becomes kinematically accessible.

Finally, for $\tan \beta = 10$ and $A_0 = 0$ in Fig. 2b, the distinguishing feature is that $\tilde{\tau}_1$, the lighter of the two $\tilde{\tau}$, can be significantly lighter than the sleptons of the e and μ families. This is because of the $\tilde{\tau}_L$ - $\tilde{\tau}_R$ mixing induced by the τ Yukawa interactions, which are enhanced for the larger value of $\tan \beta$. The region in the upper left corner is excluded since, there, the $\tilde{\tau}_1$ would be the LSP. We also note that over the entire range of parameters in Fig. 2b that are allowed by current experiments, H_ℓ is too heavy to be discovered at LEP II. It is also interesting to see that the Higgs spoiler mode for the 3ℓ signal is never open in Fig. 2, although the $\tilde{Z}_2 \rightarrow Z\tilde{Z}_1$ spoiler opens up near $m_{1/2} \sim 250$ GeV.

To summarize, we have examined collider phenomenology of minimal supergravity GUTs with radiative electroweak symmetry breaking. Within this framework, the masses and couplings of all the sparticles are fixed in terms of just four additional SUSY parameters. As a result, cross sections for various supersymmetric processes become correlated. ISAJET 7.10 provides the option of incorporating SUGRA mass relations and mixing patterns. While SUSY search strategies for specific processes remain essentially the same as in the MSSM framework, constraints from different searches frequently complement one another in the sense that they probe different regions of the SUGRA parameter space. For instance, the hatched line in Fig. 1a, which is obtained by combining the sneutrino and chargino mass limits from LEP experiments with the limit on the gluino mass from the Tevatron denotes the boundary of the region currently excluded by sparticle searches. Fig. 1 and Fig. 2 give a graphical summary of our results as a function of SUGRA parameters. We see that the particular processes which offer the largest reach for SUSY discovery are sensitive to all these parameters. While the the search for sleptons at LEP II and the search for hadronically quiet trilepton events from $\tilde{W}_1\tilde{Z}_2$ production at the main injector upgrade of the Tevatron are generically important probes, the search for charginos at LEP II plays an important role when $\mu > 0$ or when $\tan \beta$ is large. On the other hand, the search for scalar tops provides the potential for exploring regions of parameters not accessible by other searches when stop mixing effects are large (as in Fig. 2a). It is also interesting to see that over large regions of parameter space several signals must simultaneously be present at the Tevatron and LEP II.

Although, within this framework, the search for gluinos and squarks at the Tevatron, which may probe gluino masses up to about 300 GeV, is somewhat less competitive than other searches, we cannot overstress the importance of direct \tilde{g} and \tilde{q} searches: comparison of $m_{\tilde{g}}$ with $m_{\tilde{W}_1}$, or of $m_{\tilde{q}}$ with $m_{\tilde{\ell}}$ would serve as crucial tests of the assumed unification of gaugino and sfermion masses. In a similar vein, it is also important not to abandon “MSSM” analyses where the values of μ and m_{H_p} are independently input, or the relation between different squark and slepton masses relaxed. An optimal procedure may be to use SUGRA models to provide the default values of “MSSM” input parameters, and then to test the sensitivity of the resulting predictions on the various SUGRA relations. We conclude by noting that the observation of sparticles would not only be a spectacular new discovery, but that a measurement of their properties in experiments at the Tevatron and LEP II could serve as a window to physics at the unification scale.

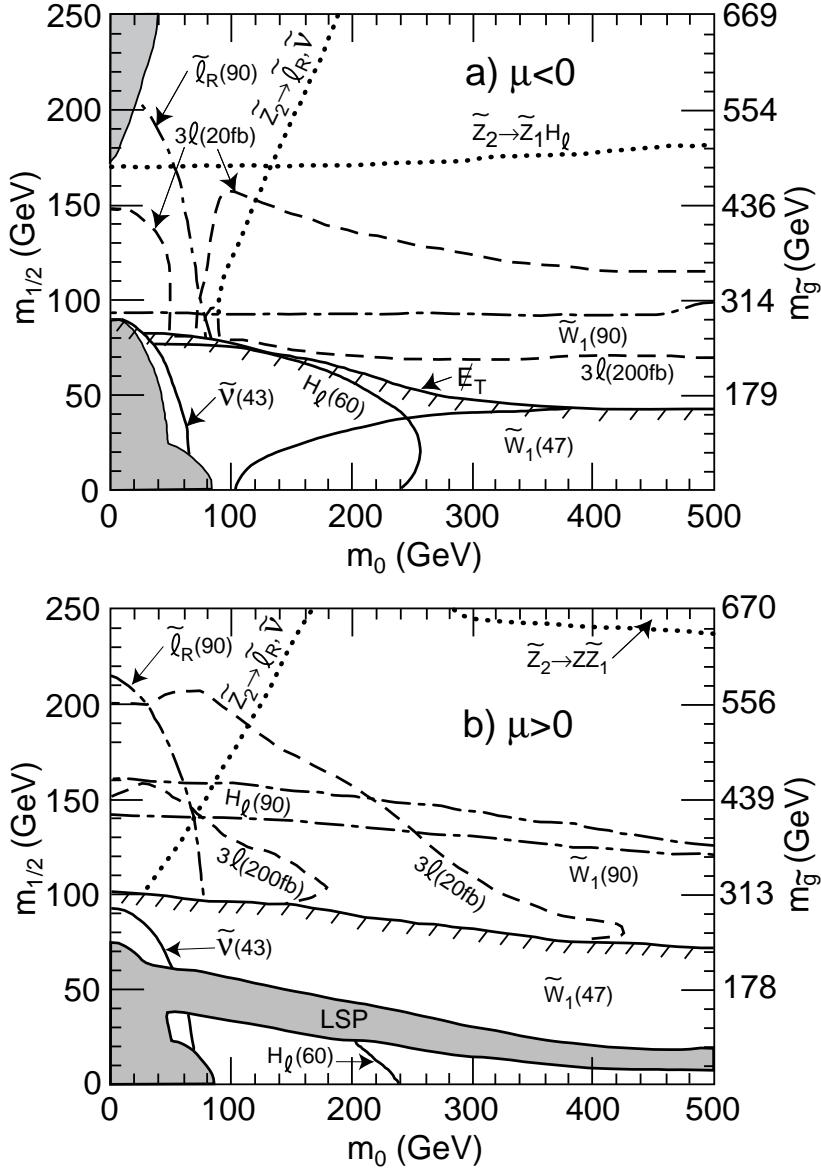
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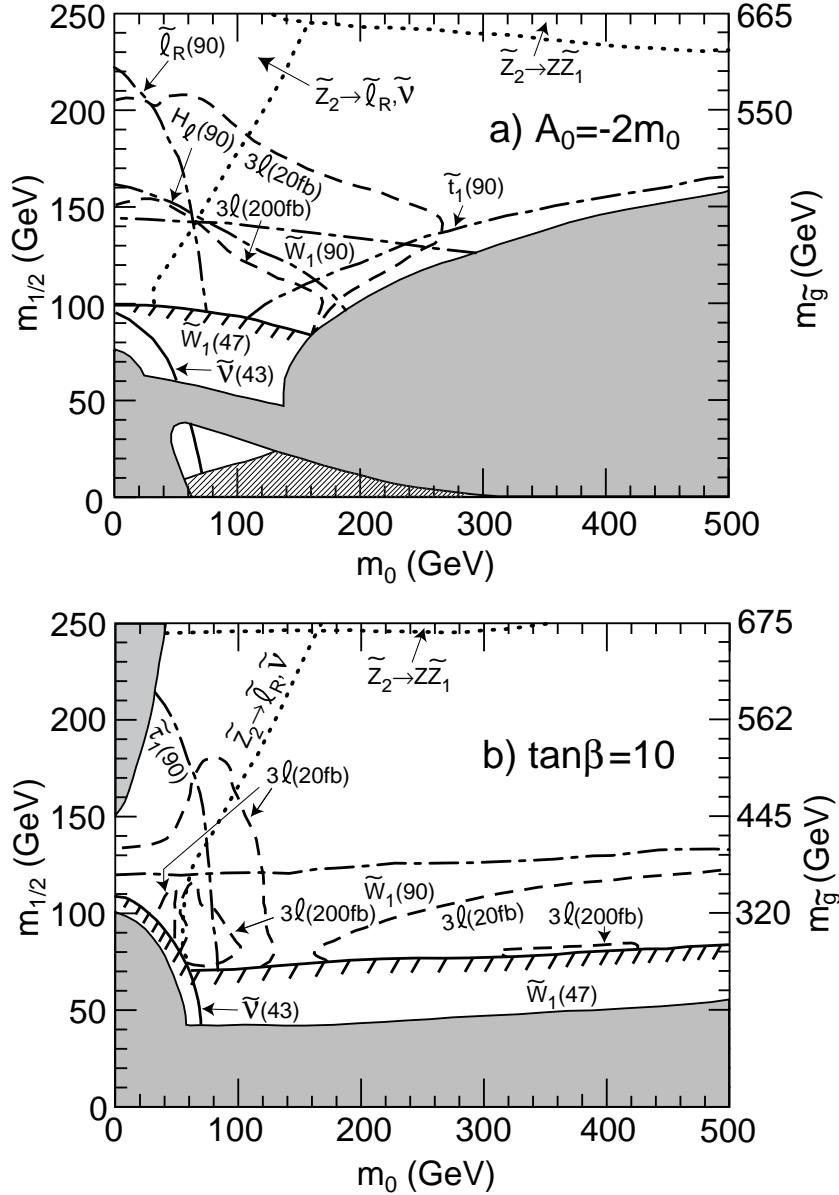
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FIG. 1. Excluded regions and the reach of LEP II and the Tevatron within the framework of the minimal supergravity model with radiative electroweak symmetry breaking. We show the results in the $m_0 - m_{1/2}$ plane for $A_0 = 0$, $\tan \beta = 2$ and *a*) $\mu < 0$ and *b*) $\mu > 0$. The shaded region is excluded for theoretical reasons discussed in the text, while the region below the hatched line is excluded by the experimental constraints from LEP and Tevatron. The area below the dashed-dotted lines labeled $\tilde{\ell}_R(90)$, $\tilde{W}_1(90)$ and $H_\ell(90)$ [$m_{H_\ell} < 90$ GeV over the whole plane exhibited in case (a)] will be probed at LEP II via direct searches for sleptons, charginos, and the lightest Higgs scalar, respectively, while the region below the dashed lines should be accessible via the isolated trilepton search for $\tilde{W}_1 \tilde{Z}_2$ events at the Tevatron as discussed in the text. We terminate these dashed and dashed-dotted lines at the hatched boundary for reasons of clarity. Finally, the dotted lines denote the kinematic boundary of various two body \tilde{Z}_2 decays that significantly alter the phenomenology.



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FIG. 2. The same as Fig. 1 except for *a*) $A_0 = -2m_0$, $\tan\beta = 2$, $\mu > 0$ and *b*) $\tan\beta = 10$, $A_0 = 0$, $\mu < 0$. The large shaded region in case (a) is excluded because $m_{\tilde{t}_1}^2 < 0$, while in the slanted line covered region, $m_{\tilde{t}_R}^2 < 0$. In case (b), H_ℓ is too heavy to be detected at LEP II, for parameter values not already excluded by experiment.